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Pre-design of a mini CSP plant

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Abstract

The REELCOOP project funded by the European Union aims at developing and demonstrating three small scale solar electricity generating units with two of them using thermal power cycles and one using PV. The system described here includes parabolic trough collectors and an organic Rankine cycle (ORC), enhanced by a biogas boiler and a thermal storage. With a net aperture area of 979 m² the solar field supplies saturated steam at 170°C to the ORC which produces a nominal electrical output of 60 kW. Excess thermal energy will be stored in a novel vertical spiral plate heat exchanger with phase change material. Additionally a biogas boiler can deliver steam at the desired pressure to the ORC. Detailed planning of the hydraulic circuit is ongoing. Several components, mainly solar field and ORC, are under fabrication so that their construction on-site is expected for next winter, followed by commissioning envisaged for March 2015.

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1. Introduction

Small scale solar electricity generation is a technology which is of interest for many communities in the sun belt area. The REELCOOP project funded by the European Union aims at developing and demonstrating three such systems with two of them using thermal power cycles and one using PV. The system described here includes parabolic trough collectors and an organic Rankine cycle (ORC), enhanced by a biogas boiler and a thermal storage. It will be installed at the École Nationale d'Ingénieurs de Tunis (ENIT), in Tunisia. This installation will then be used, not only for demonstration, but also for training students on the involved renewable techniques. The design is ongoing and will be followed by installation and commissioning planned for March 2015.

2. General layout

Solar power generation is typically accomplished in large plants in the range of several dozens of MW, to reduce electricity costs by economies of scale. The scope of the REELCOOP project is to develop a solar thermal electricity generating system of about 60kW for small scale power generation. Firstly a steam engine of the company Voith had been considered, but it needs to be supplied with superheated steam at more than 300°C, which would have been very challenging to realise within the project. Instead an ORC was found in the right power range which would only need an inlet temperature of about 170°C. This is more adapted to the temperature range of concentrating process heat collectors mostly not equipped with vacuum receivers.

The nominal gross efficiency of an ORC of the company Zuccato Energia reaches 13 to 15%. The solar field size has been adapted to the thermal power demand and designed for a net collector surface of 979 m². Due to original planning and because the development of a Phase Change Material (PCM) storage is foreseen in the project, the heat will be transferred via saturated steam. Accordingly, the solar field is designed for direct steam generation (DSG) mode with the recirculation concept (Figure 1). At nominal operation sub-cooled water at about 140°C enters the collectors, where it is heated to 170°C and partially evaporated. The water content is then separated in a steam drum and recirculated. The saturated steam leaves the steam drum, and is then condensed and sub-cooled to 80°C in two plate heat exchangers, in order to drive the ORC cycle. To demonstrate how electricity can be provided in times of low radiation, a biogas boiler and a thermal storage are integrated. The storage module is designed with an innovative spiral concept. Loading is foreseen with 180°C steam temperature and during unloading steam at 160°C shall be provided to the ORC. For this temperature range several PCMs are under study. The remains of the canteen at ENIT are foreseen to be treated in an anaerobic digester. The gas will be stored and burned in a biogas boiler to supply steam at the pressure desired for the turbine.

To avoid corrosion, a closed system is planned instead of the typical open process steam supplies. The installation will be full of water when cold. In the expansion tank a nitrogen filling at a pressure slightly over ambient pressure ensures that air cannot enter the piping system. During start-up mainly the amount of water in the steam piping (red lines in Figure 1) needs to be removed. The expansion tank takes this water volume and has been dimensioned accordingly. The steam inlet temperature for the ORC under nominal operation is about 160°C; accordingly the solar field runs between 160°C and 170°C. To load the storage, a higher temperature of 180°C is foreseen for the solar field.

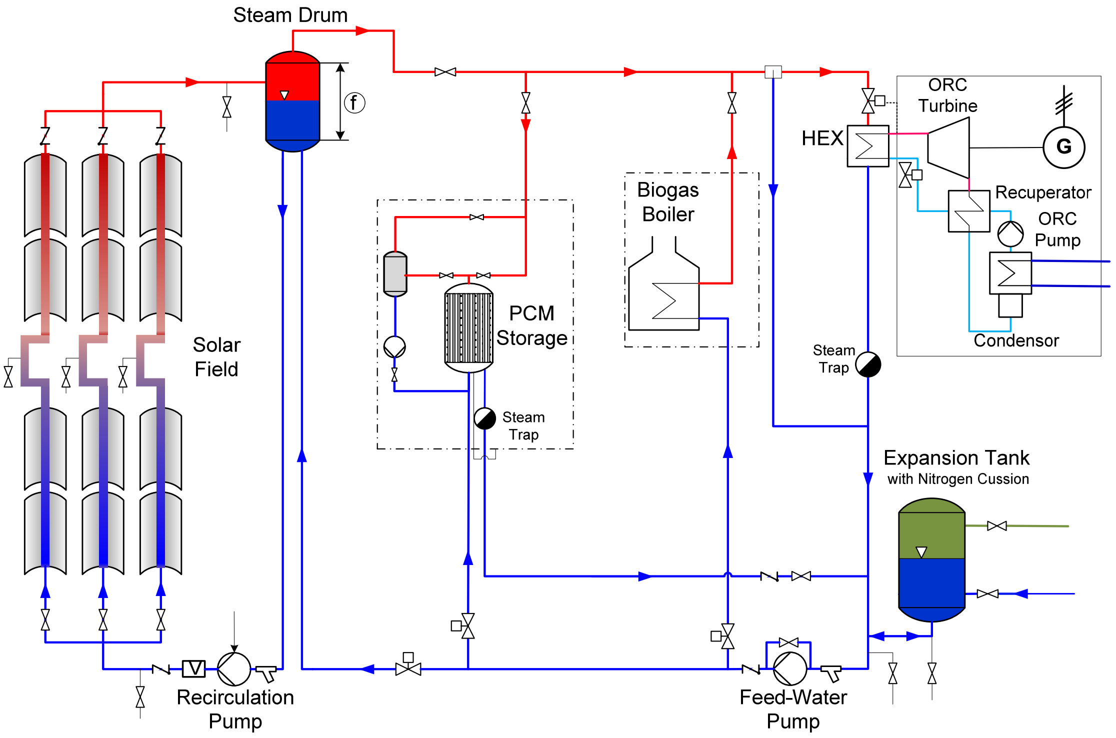

Fig. 1. Plant layout with steam lines in red, condensate and feed water lines in blue

3. Solar collector field

3.1. Description of the solar collectors

The solar field is composed by 12 PTMx/hp-36 solar collectors manufactured by the Italian company Soltigua.

The suffix “hp” in the collector name stands for the “high pressure” version, which is appropriate for direct steam generation and the number 36 stands for the collector length of 36m. Each collector is composed by one drive system including tracking control and 6 modules, with a width of 2.37m and a length of 5.95 m at the outer glass edges. A section of the collector is shown below in Figure 2.

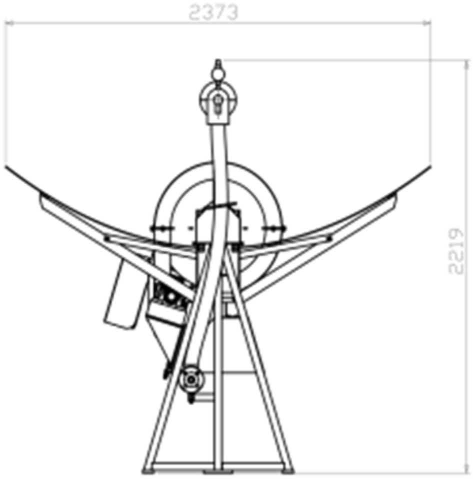

Fig. 2. Section of Soltigua's collector

The mirrors are made of glass and silver with a high reflectance with the glass tempered to ensure a high safety level. They have enough stiffness to be carried at four points by a steel structure below.

The small aperture width simplifies the collector requirement for cleaning and ease of use and also reduces the wind forces transmitted to the foundations. To avoid corrosion in an outdoor environment the metallic structure is hot dip galvanized.

The receiver includes both an absorber tube and an outer glass tube, but it is not evacuated. The absorber pipes are bolted to each other to avoid welding during the installation. In order to be operated under pressure for DSG generation, the receiver tubes are certified according to the pressure equipment directive (PED) of the EU.

Each collector has an independent drive system which allows tracking the sun during the day, managed by an on board electric control panel. To detect and avoid excess temperatures a temperature sensor is connected to the control. All on board control panels are wired to a general control panel, which controls the whole solar field and connects it to further safety sensors such as wind and radiation sensors.

The solar field can run completely automatically and is controlled by an industrial PLC. The PLC starts tracking in the morning and controls all working parameters, to detect alarms or unusual situations. In such cases, the system exits its automatic cycle to go back in a stowed and safe position.

On-going work is aiming at certifying the whole collector as a self-standing machine under PED regulations.

3.2. Solar field layout

The solar field size of 979 m² has been determined after the thermal energy necessary to drive the ORC, but it also is limited by the available project budget. To avoid a high pressure drop in the solar field not all collectors can be connected in series, and so parallel loops need to be considered. Various configurations between 1 and 12 parallel collector rows have been investigated using equations for water/steam mixture with the program Ebsilon. Figure 3 displays a high pressure drop for all 12 rows in series and as expected the lowest for 12 parallel rows. To lower costs, a low amount of parallel loops is desirable. A compromise of 3 parallel loops has therefore been selected.

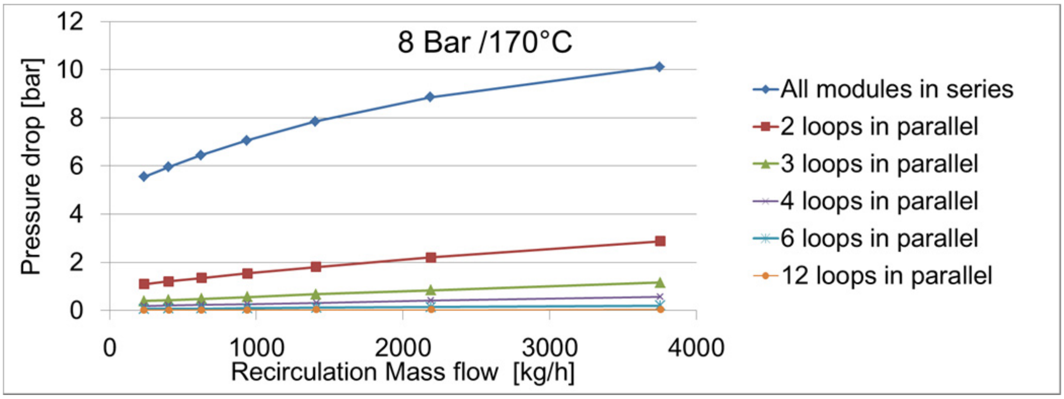

Fig. 3. Calculated pressure drop for various loop configurations depending on recirculation mass flow rate

DSG installations for saturated steam have been realised in the so-called recirculation mode, as it is planned here. Each collector loop is supplied with more water than will be evaporated, so that a dry-out of the absorbers can be avoided. Evaporation cannot be controlled well and the absorbers would undergo high thermal and mechanical stress. The water content coming out of the collector field is separated from the steam in the steam drum and is recirculated to the solar field.

To counteract flow instabilities between parallel loops, in power plants with direct steam generation, mass flow control with automatic valves has been used up to now. Flow instabilities occur because a higher evaporation rate causes higher pressure drops. If one of the loops receives more energy and evaporates more water than the others, it will suffer a higher pressure drop. Hence less water will flow into it and more into the others, aggravating the effect.

Using hand valves instead of automatic valves can reduce the complexity and the cost. Additionally three parallel rows suffer less flow instability than a larger number of parallel rows. It is foreseen to cause a pressure drop in the valves by partially closing them, so that the fluctuations in the pressure drop due to different evaporation in the loops will not cause severe mass flow reduction in one of the loops.

4. ORC Description

The ORC unit is driven by the steam received from the solar field. As the units of Zuccato were initially built for using waste heat gas or pressurised water, the heat exchangers and control have been adapted. The steam is fed to the system through a 2-way valve. It reaches the two heat braze-welded exchangers (evaporator and preheater) and then it goes back to the source in condensate form.

The organic fluid is stored in a tank and pumped to the preheater and then to the evaporator, where it changes its phase to vapour, in order to run the turbine. The fluid is then condensed in a heat exchanger and sent to the collection tank again.

The unit is designed to be flexible: the turbine’s control system allows variable speed, optimising the electrical yield in case of partial load conditions.

A new generator design has lower friction losses and, better cooling performance, due to an innovative cooling system, and thus high electrical yield.

The unit is compact, as shown in the layout (Figure 4).

Performance of the ORC strongly depends on the recooling temperature. Therefore, and due to the lower investments costs, a wet or hybrid cooling tower is envisaged.

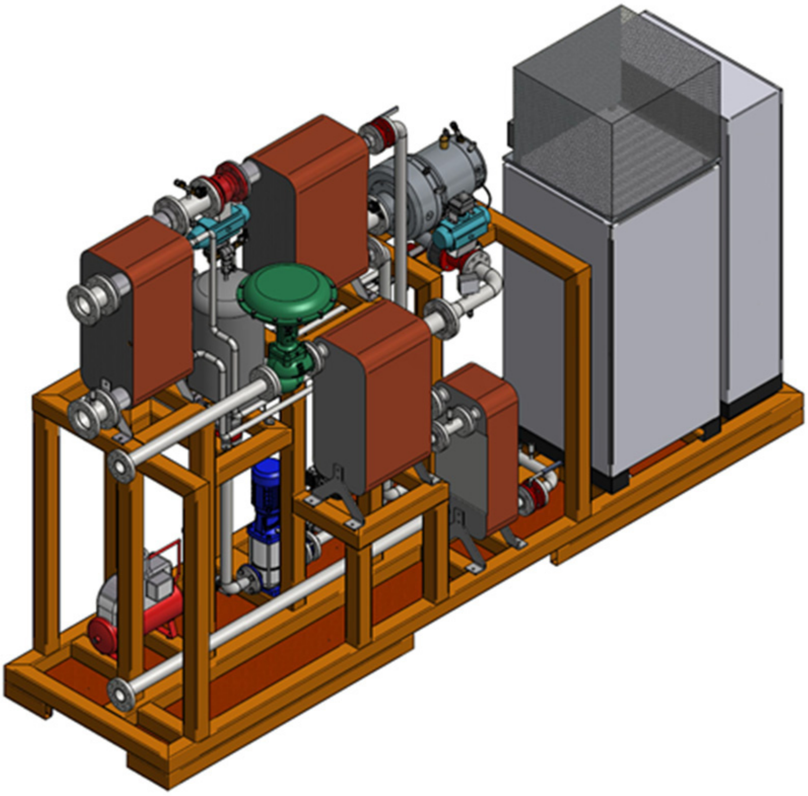

Fig. 4. Design of ORC on rig with all components

5. Description of the biogas boiler

The boiler is foreseen to produce steam at the desired pressure of about 7 bars, fired with gas from a biogas digester. The gas will be produced through an anaerobic digestion of about 350 kg of waste per day from the canteen at ENIT. Due to the project constellation the gas is not being fired in a more efficient combustion engine. The use of a biogas boiler instead of other technologies such as biomass combustion, is justified by local availability of organic residues and associated low cost, as well by contributing to the improvement of environmental and living conditions by managing the problem that waste disposal represents . A combustion engine would make more efficient use of the biogas. The project though aims at demonstrating the integration of a boiler into a steam cycle powering a turbine.

First tests with canteen waste in a 1m³ experimental digester at mesophilic temperatures of about 37°C showed a rising gas production for the first 14 days and then a decline during the next ten days. To homogenise the production 5 digesters will be filled in succession. A gasometer will store the gas.

A high amount of low temperature waste heat is available during operation of the ORC. It is foreseen to heat the walls of the digester to enhance the digestion process.

6. Description of the storage

Since DSG technology entails water condensation/evaporation processes, isothermal storage/release of energy is the most appropriate approach. This implies to store energy as latent heat with phase change materials (PCM's) undergoing state transitions at temperatures close to the steam working conditions, unlike current commercial storage systems, which deal with storing sensible thermal energy by a temperature change in the storage medium.

When a material undergoes a phase change from liquid to solid, the freezing front progress takes place only by conduction, which means that heat transfer efficiency is limited by the thermal conductivity of the solid phase. Unfortunately, the most used PCMs have low thermal conductivities (around 0.5 W/mK) affecting significantly the power density of the whole storage system. To date, many solutions have been proposed for overcoming these drawbacks: micro and macro PCM encapsulation, [4], use of nanoparticles, [5],[6], improvement of the solid phase thermal conductivity by using composite materials, [8], metallic PCM's [9] or heat pipes [10] and increase the heat transfer area by means of fins or extended surfaces [11] but also by having a large energy exchange surface by unit volume, [12]. The latest is the concept on which the storage prototype here considered is based. Its geometry is inspired on vertical spiral plate heat exchangers (SPHE) geometry. While in spiral heat exchangers two fluids exchange energy in counter-current flowing through spiral channels, in the new concept for latent thermal energy storage, the PCM is located in one of the spiral channels and the heat transfer fluid flows along the other one (Figure 5).

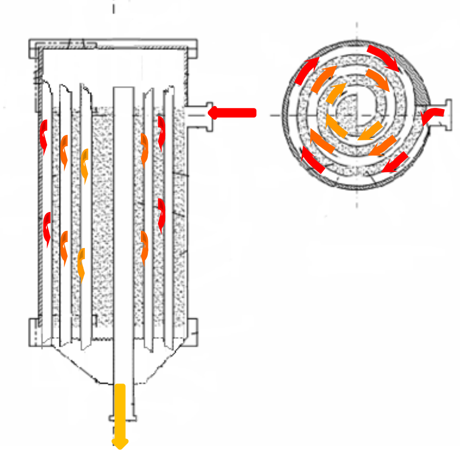	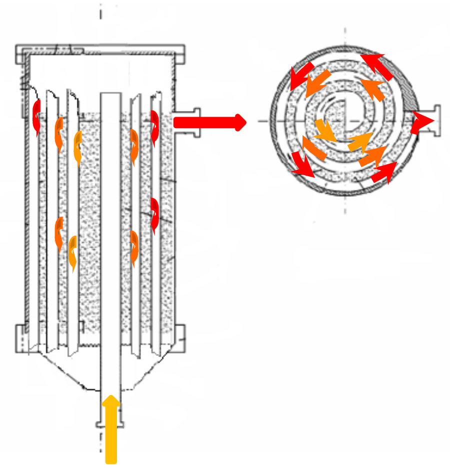
CHARGE: HTF goes into the storage module as saturated steam through the lateral upper opening and flows through the spiral channel from the biggest diameter to the smallest one. In this flow, HTF loses energy by melting the solid PCM, placed in the alternate spiral channel, and condensates.	DISCHARGE: HTF goes into the storage module as saturated water entering the module from the bottom opening and flows through the spiral channel from the smallest diameter to the biggest one. In this flow, HTF gains energy by solidifying the liquid PCM, and exits the module through the lateral upper opening.

Fig. 5. Spiral storage, Left picture: Charging of storage. Right picture: Discharging of storage

The PCM to use will have to be the one that better fits to the ORC, which, under today design conditions and available safe material, implies to be D-Manitol.

7. Description of infrastructure

The system will be installed at the École Nationale d'Ingénieurs de Tunis (ENIT) in Tunisia (Figure 6). A ground of 27 000 m^2 close to ENIT is available to install all components of the system: solar field, control building, cooling system and biomass. Water for the cooling system will be provided; electrical connections and data transfer will be established.

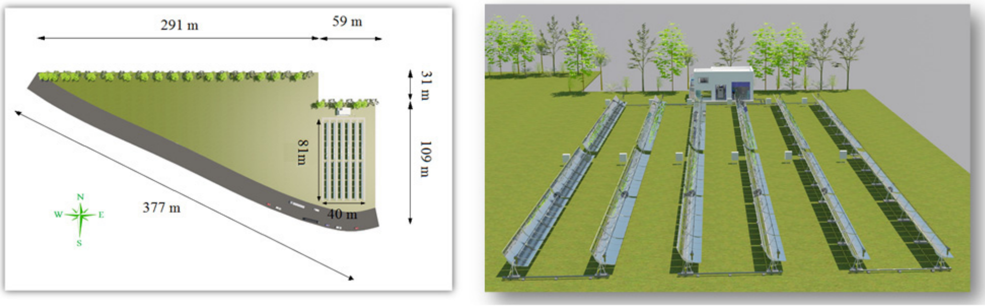

Fig. 6. Left picture: land area. Right picture: solar field and building

The solar field will be erected south of the building. Each collector of the solar field has an on-board electric panel.

The main electricity supply goes to an uninterruptable power supply (UPS) and then to the main control panel, where the control PLC is installed. Each on-board electric panel (QBM) is connected to the solar field main panel, with both a data and a power cable.

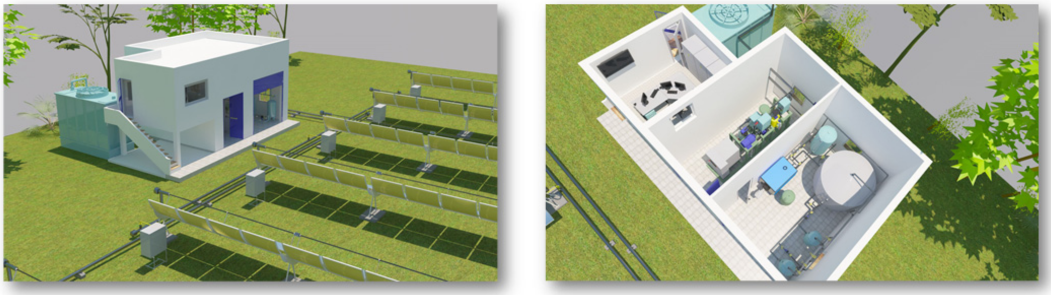

Fig. 7. Left picture: solar field and building. Right picture: building

The building does not include the biomass storage, cooling tower and anaerobic digester.

The main components in the control building are: Organic Rankine Cycle subsystem including the turbine, steam drum and pumps, control room, electric panels and air conditioner for the ORC turbine (Figure 7).

8. Performance of the system

The system performance of solar field and Organic Rankine Cycle (ORC) has been evaluated through numeric simulation, using two distinct software codes for the Solar Field (SF): Greenius [1] and Ebsilon [2]. The EES software [3] was used for the ORC. The solar collector efficiency function $\eta = IAM \times 0.747 - 0.64 \times \Delta T/DNI$ as well the ORC turbine performance curve according to information given by Zuccato were used in the simulations. The meteorological data were collected locally in Tunis during one year with the direct normal radiation being derived from diffuse and global radiation measurements. The simulations were carried out with the assumption of the system running on solar-only mode. This means neither biogas boiler nor thermal storage is included in this preliminary performance estimation, as these components have not been defined in detail yet. Thermal losses in piping and thermal capacities were included. The key results are presented in table 1 while figure 8 shows the performance characteristic of a typical day. The agreement between the results of both simulation tools is good. The mean annual efficiency of about 36% for the SF and 10.5% for the ORC lead to a global system efficiency near 4%.

As the specifications of the pumps, also for re-cooling, are not yet defined only gross efficiency is calculated. Due to the part load restrictions of the ORC or due to excess thermal solar field output, about 18% of the collected heat must be dumped if thermal storage is not considered. It is expected that the system efficiency and the number of running hours will increase due to the hybridisation of the system with biogas and the addition of a storage tank.

Table 1. Key simulation results

		Greenius	Ebsilon
Direct Normal Irradiation	[kWh/(m^{2}a)]	1978	
Annual Heat Generation	[MWh$_{th}$]	682	725.8
Specific SF Output	[kWh$_{th}$/m^2]	692.8	737.6
Mean SF Efficiency	[%]	35	37.3
Annual Power Generation	[MWh]	72.6	76.5
Mean ORC Efficiency	[%]	10.6	10.5
Annual ORC Running Hours	[hr]	1540	1574
Mean System Global Efficiency	[%]	3.7	3.9
Dumping Rate	[%]	18.0	19.4

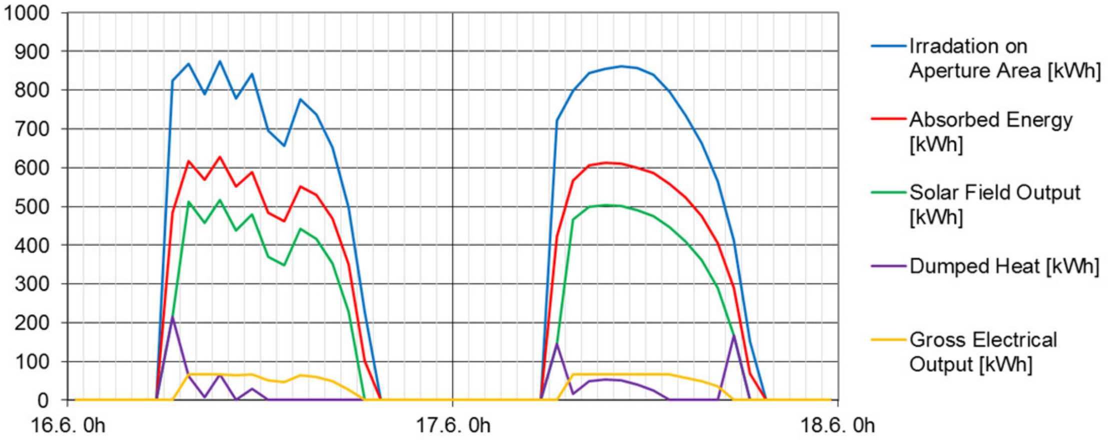

Fig. 8. Characteristic development of system performance on June 16-17

9. Summary

The layout of a small scale solar thermal system combined with thermal storage and a biogas boiler to produce electricity has been described. Whilst the solutions for storage and biomass are still under investigation, the solar field and ORC have been defined. The integration of the components is planned as a closed hydraulic circuit with direct steam generation.

At ENIT the system will especially demonstrate the technology options and how they can be operated in combination to optimise the electrical output. It will also serve to train students to disseminate knowledge on the technologies. Therefore the system will not run during the whole year and the annual output calculated in chapter 8 has to be regarded as theoretical.

The mean electrical system efficiency is low compared to greater CSP installations or PV. Therefore the heat dissipated by the power unit should be exploited in commercial installations.

A high amount of low temperature heat is dissipated and can only for a small share be used to enhance the anaerobic digestion. Clearly only a power unit in cogeneration mode will be of economic interest, which can provide its waste heat at a temperature level, that a consumer can make use of. Typically this could be around 100°C.

Within the project REELCOOP detailed planning of the hydraulic circuit is ongoing. Several components, mainly solar field and ORC, are being fabricated so that their construction on-site is expected for next winter, followed by commissioning envisaged for March 2015.

Acknowledgements

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References

[1] Greenius. DLR. http://freegreenius.dlr.de/
[2] EBSILON®Professional. STEAG Energy Services GmbH. http://www.steag-systemtechnologies.com
[3] EES: Engineering Equation Solver. F-Chart Software. http://www.fchart.com/ees/
[4] Zhao W., Zheng Y., Sabol J. C., Chen J. C., Tuzla K., Oztekin A., Misiolek W., Neti S.: Thermal energy storage for solar systems using NaNO3 as encapsulated phase change material. 12th International Conference on Energy Storage, Innostock.2012, Lleida (Spain) May 2012.
[5] Cingarapu S., Singh D., Timofeeva E. V., Moravek, M. R.: Nanofluids with encapsulated tin nanoparticles for advanced heat transfer and thermal energy storage. International Journal of Energy Research 2013, doi: 10.1002/er.3041.
[6] Sciacovelli A., Colella F.,Verda, V.: Melting of PCM in a thermal energy storage unit: Numerical investigation and effect of nanoparticle enhancement. International Journal of Energy Research 2012; doi: 10.1002/er.2974.
[7] Steinmann W. D., Tamme R.: Latent heat storage of solar steam systems. Journal of Solar Energy Engineering-Transactions of the ASME 2008; 130: 011004-1-5.
[8] Pincemin S., Olives R., Py X., Christ M.: Highly conductive composites made of phase change materials and graphite for thermal storage. Solar Energy Materials and Solar Cells 2008; 92: 610-613.
[9] Hunt A. J., Carringon K. R.: Metal Latent Heat Thermal Storage System. SolarPACES 2012 Conference, Marrakech (Morocco) September 2012.
[10] Nithyanandam K., Pitchumani R.: Computational studies on a latent thermal energy storage system with integral heat pipes for concentrating solar power. Applied Energy 2013; 103: 400-415.
[11] Steinmann W. D., Tamme R.: Latent heat storage of solar steam systems. Journal of Solar Energy Engineering-Transactions of the ASME 2008; 130: 011004-1-5.
[12] Rivas, E.; Rojas, E.; Bayón, R., Innovating storage with PCM: Progress in the design of a new prototype, SolarPACES Conference, September 2012.